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The Application Of Advanced Technology To Improve Air Bag Performance

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ABSTRACT

In December 1996 the National Highway Traffic Safety Administration (NHTSA) and The National Aeronautics and Space Administration (NASA) signed a memorandum of understanding for NASA to assess the capability of advanced technology to reduce air bag inflation-induced injuries and increase air bag effectiveness. The Jet Propulsion Laboratory (JPL) was selected to conduct the assessment. The assessment is now complete; this paper summarizes the key results.

The critical parameters affecting air bag performance were derived from a functional analysis of air bag operation. They were the focus of all subsequent analyses.

Air bag performance was established from crash, sled and static tests and simulations. Sensitivities of the critical parameters, based on the air bag performance data, were established to guide the advanced technology assessment.

Advanced technologies were surveyed to determine their technical characteristics and state of readiness. These characteristics together with the air bag performance sensitivities were combined with alternative technology application strategies to estimate reduction of inflation-induced injuries and increased air bag system effectiveness.

The paper presents the critical parameters and summarizes the analysis of air bag performance, assessment of advanced technology characteristics and their potential for reducing air bag inflation-induced injuries and increasing air bag effectiveness.

INTRODUCTION

As a result of the concern for the growing number of air-bag-induced injuries and fatalities, the administrators of the National Highway Traffic Safety Administration (NHTSA) and the National Aeronautics and Space Administration (NASA) agreed to a cooperative effort that "leverages NHTSA's expertise in motor vehicle safety restraint systems and biomechanics with NASA's position as one of the leaders in advanced technology development... to enable the state of air bag safety technology to advance at a faster pace..." They signed a memorandum of understanding for NASA to "evaluate air bag performance, establish the technological potential for improved (smart) air bag systems, and identify key expertise and technology within the agency (NASA) that can potentially contribute significantly to the improved effectiveness of air bags." NASA is committed to contributing to NHTSA's effort to "(1) understand and define critical parameters affecting air bag performance, (2) systematically assess air bag technology state of the art and its future potential, and (3) identify new concepts for air bag systems." The Jet Propulsion Laboratory (JPL) was selected by NASA to respond to the memorandum of understanding by conducting an advanced air bag technology assessment.

JPL's interpretation of its mandate led to the following activities. We analyzed the nature of the need for occupant restraint, how air bags operate alone and with safety belts to provide restraint, and the potential hazards introduced by that technology. This yielded a set of critical parameters for restraint systems. We examined data on the performance of current air bag technology. Finally, we searched for and assessed how new technologies could reduce the hazards introduced by air bags while providing the restraint protection that is their primary purpose.

The technological challenge is to provide more robust occupant restraint systems, including air bags, i.e., systems that are safer and more protective over a wide range of crash severities and occupant categories. Stated simply, air bag protection must be more robust with respect to variation of critical parameters that govern air bag performance.

CRITICAL PARAMETERS

An advanced system must be better than current systems at obtaining and processing information. It will have to predict crash severity, establish the size and weight of the occupants, determine their proximity to the air bag, and sense whether or not they are belted. Air bag inflation will need to vary in response to crash and occupant variation. The parameters that determine air bag advanced technology requirements were established by a functional analysis of a complete crash scenario. The functions of an occupant protection system were analyzed according to the total set of interactions that occur during a crash. These include interactions between the obstacle and the vehicle, the vehicle and the restraint, and the restraint and the occupant. This analysis assured that all major functions were accounted for. It produced a set of basic parameters classified by the information provided about the crash and the occupants and the air bag system response. We defined a subset of the basic parameters that are fundamental to air bag operation. We call them the "critical parameters." They are:

Input Information

- Crash severity and vehicle crash pulse shape and duration
- Driver and passenger characteristics including height, weight, age, and gender
- Belt or child safety seat use
- Proximity of the occupant to the air bag module

Air Bag Response Characteristics

- Time to deployment decision: sensor reaction and information processing
- Time and rate of air bag inflation, which is related to inflator parameters
- Inflator parameters, such as inflator mass flow rate
- Air bag design, including configuration, compartmentalization, venting, materials, and fold

Reliability

AIR BAG PERFORMANCE

Air bag performance was analyzed using an injury risk assessment. The injury risk assessment methodology for evaluating the effect of changes in governing parameters of the air bag system on the risk of occupant injury is illustrated in Figure 1. The critical parameters are shown in the figure.

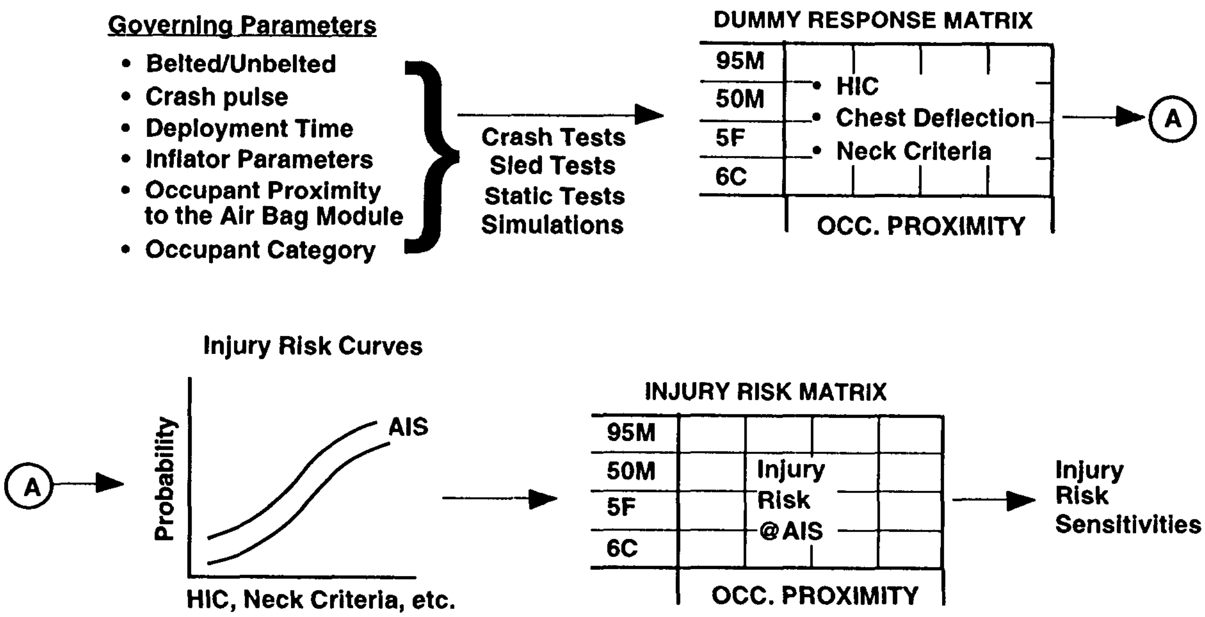

Figure 1. Injury Risk Assessment Methodology

The dummy response matrix shown in Figure 1 is derived from vehicle crash tests, sled tests to simulate vehicle crashes, static tests and computer simulations. The preferred source of dummy response data is vehicle crash tests; however sled tests, static tests, and simulations can show dummy response to the critical parameters.

The dummy response matrix is transformed into an injury risk matrix by means of injury risk curves. The injury risk matrix presents the injury risk of different occupant categories, i.e., 6-year-old child, 5th-percentile female, 50th-percentile male, and 95th-percentile male. Injury risk can be evaluated for selected sets of critical parameters so that sensitivities of injury risk to changes in critical parameters can be determined. These sensitivities will allow the impact of an advanced technology on injury risk across occupant categories to be assessed.

Data and information to support the generation of the dummy response sensitivities of Figure 1 were obtained from NHTSA publications, discussions and test results provided by Transport Canada, and discussions and information provided by the U. S. automobile manufacturers and air bag suppliers. In particular, data from car crash tests were provided by Transport Canada to characterize sensitivities of dummy response with respect to variation in crash pulse, inflator output, and proximity for the various occupants with three-point belts alone, and air bags plus three-point belts. In addition, results of computer simulations that were calibrated with crash or sled tests were provided by a U. S. automobile manufacturer. Additional car crash test results and sled test results were provided by U. S. automobile manufacturers and were also taken from various NHTSA publications and other references in the open literature.

Table 1 shows 5% female injury risk for a deformable offset barrier test and a rigid frontal barrier test for six vehicle types with three point belts and airbags. For four of the six vehicle types, neck injury risk is higher in the DOB crash test. In five of the six vehicle types tested, the neck injury risk is greater than 10% for either the DOB or RFB crash test.

The injury risk for the 50% male in RFB 30 Tests was determined for the same vehicle types as shown in Table 1. The 50% male injury risk is low in all cases.

A paired comparison, with and without air bag deployment, of injury risk for the belted 5% female for five car models in deformable offset barrier tests is shown in Table 2. Also shown is the time of deployment initiation of the air bag. In the three cases where time of deployment initiation exceeds 40 ms, the neck injury risk is very high. Late deployment allows the occupant to move closer to the air bag, thereby exacerbating the membrane effect with the attendant increase in neck loading.

Table 3 shows 5% female injury risk for the same vehicle model for a baseline air bag with a three point belt, a depowered air bag, and a three point belt alone. Note that the lowest injury risk for the neck and the head is obtained with the three point belt alone, and the lowest chest deflection is also with the three point belt alone. Even though lowest chest deflection is obtained with the three point belt alone, the injury risk is higher because of the different injury risk curves used for air bag loading and shoulder belt loading. The depowered air bag does reduce the neck injury risk significantly relative to the baseline airbag, but the injury risk performance of the belt alone is superior to either the baseline or depowered air bag with belt for the 5% female in the DOB 25 test.

Table 4 shows the results of static air bag deployment tests for the 6-year old child dummy. Depowering by 30% does not reduce neck injury risk to acceptable levels. The normal power and 30% depowered test results show high levels of neck injury risk, which is consistent with the evidence from incidents in which children have experienced fatal neck injuries from being in close proximity to deploying air bags.

Table 1. Injury Risk for 5% Female Drivers in Rigid Frontal Barrier and Deformable Offset Barrier Vehicle Crash Tests Performed by Transport Canada

TC Test Number	Test Vehicle	Barrier Type (mph)	Restraint System	Head Injury Risk (%)	Neck Injury Risk (%)	Chest Injury Risk (%) AB¹/Belt²
TC96-101	A-96	RFB(30)	3PB+AB	4.4	37.2	10.0/30.6
TC96-021	A-96	DOB(25)	3PB+AB	3.4	50.1	0.0/5.7
TC96-102	B-96	RFB(30)	3PB+AB	0.4	94.4	0.1/11.7
TC96-211	B-96	DOB(25)	3PB+AB	0.5	100	3.2/23.3
TC96-112	D-96	RFB(30)	3PB+AB	0.4	71.3	0.0/6.6
TC95-206	D-95	DOB(25)	3PB+AB	0.7	99.4	0.0/5.2
TC96-114	E-96	RFB(30)	3PB+AB	0.2	2.1	0.0/4.5
TC96-025	E-96	DOB(25)	3PB+AB	0.1	1.8	0.0/4.9
TC97-110	E-97	RFB(30)	3PB+AB	0.1	2.2	0.0/11.3
TC96-122	G-96	RFB(30)	3PB+AB	0.1	19.1	12.6/32.5
TC95-021	G-95	DOB(20)	3PB+AB	1.4	64.2	0.0/7.8
TC96-115	F-96	RFB(30)	3PB+AB	0.4	10.6	0.2/12.7
TC96-002	F-96	DOB(25)	3PB+AB	0.1	0.8	0.0/5.7
TC96-125	I-96	RFB(30)	3PB	4.3	11.6	27.0
TC97-108	P-97	RFB(30)	3PB	0.7	19.4	56.3

3PB = Three point lap/shoulder belt
AB = Air bag
(1) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts
(2) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading
RFB: Rigid Frontal Barrier
DOB: Deformable Offset Barrier

Table 2. Response of Belted 5% Female Hybrid III Dummy in Driver Seat (Near Position) In 25 Mile Per Hour Deformable Offset Barrier (DOB25) and 20 Mile Per Hour Deformable Offset Barrier (DOB20) Car Crash Tests performed By Transport Canada

	Car Model									
	B-96		F-96		E-96		G-95	G-96	D-95	D-96
	3PB + AB	3PB	3PB + AB	3PB	3PB + AB	3PB	3PB + AB	3PB	3 PB + AB	3PB
	DOB25	DOB25	DOB25	DOB25	DOB25	DOB25	DOB20	DOB20	DOB25	DOB25
Dummy Response	TC96-211	TC96-210	TC96-002	TC96-205	TC96-025	TC96-207	TC96-021	TC95-127	TC95-206	TC95-209
Deployment initiation	100 ms*		30 ms*		40 ms*		91 ms*		56 ms*	
HIC 15	338	235	85	191	112	131	490	124	367	189
Injury Risk, AIS 4+, %	0.5	0.3	0.1	0.2	0.1	0.1	1.4	0.1	0.7	0.2
Neck Tension, N	4583	527	1225	892	1330	978	4170	809	2752	978
Neck Ext. Moment, Nm	134	21	17	8	24	7	45	9	124	14
Injury Risk, AIS 3+. %	>99.9	0.4	0.8	0.2	1.8	0.2	64.2	0.2	99.4	0.4
Chest Deflection	37.6	13.1	23.1	22.9	21.9	20	25.9	12.2	22.4	20.6
Injury Risk, AIS 3+, %					0					
AB[1]/Belt[2]	3.2/23.3	1.5	0.0/5.7	5.5	0/4.9	3.9	0.0/7.8	1.3	0.0/5.2	4.2

3PB = Three point lap/shoulder belt
AB = Air bag
(1) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts
(2) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading
*Air Bag Deployment Time

Table 3. Injury Risk Comparison for 5% Female Driver in 25 mph Deformable Offset Barrier (DOB25) Vehicle Crash Tests with Fully Powered, Depowered (3PB + AB), and No Air Bag

	Car Model		
	D-95	**D-97-D**	**D-96**
	3 PB + AB	**3 PB + AB**	**3 PB**
	DOB25	**DOB25**	**DOB25**
Dummy Response	**TC96-206**	**TC97-200**	**TC96-209**
HIC 15	367	N/A	189
Injury Risk, AIS 4+, %	0.7	N/A	0.2
Neck Tension, N	2752	902	978
Neck Ext. Moment, Nm	124	38.1	14
Injury Risk, AIS 3+. %	99.4	3.5	0.4
Chest Deflection	22.4	24.2	20.6
Injury Risk, AIS 3+, %			
AB[1]/Belt[2]	0.0/5.2	0.0/6.4	4.2

3PB = Three point lap/shoulder belt
AB = Air bag
(1) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts
(2) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading

Table 5 shows the injury risk for different occupant categories for fully powered air bags, and Table 6 shows the corresponding injury risk for depowered air bags. The 30% depowered air bag results in a drastic decrease in injury risk for 5th percentile female dummies while very slightly increasing injury risk for 50th percentile male dummies. Child injury risk is not significantly affected by this level of depowering.

Table 4. Static Sir Bag Deployment Tests by NHTSA for Configuration B-94 with 6-Year-Old Hybrid III Dummy in Three Positions Adjacent to the Air Bag Module. Dummy Positions are Shown in Reference [1]

Dummy Response	Position 1			Position 2			Position 3		
	B-94 Normal	B-94 30% Depowered	B-94 60% Depowered	B-94 Normal	B-94 30% Depowered	B-94 60% Depowered	B-94 Normal	B-94 30% Depowered	B-94 60% Depowered
*HIC 15	720	129	16	1225	238	53	683	27	2
Injury Risk, AIS 4+, %	4.8	0.1	0.0	31.3	0.3	0.1	4.0	0.1	0.0
Neck Tension, N	6184	2383	1279	6661	2069	836	2152	1257	146
Neck Ext. Moment, Nm	175	83	31	68	51	20	40	39	5
Injury Risk, AIS 3+, %	>99.9	99.8	16.0	>99.9	77.8	2.4	57.9	29.0	0.0

*HIC 15 is estimated from HIC 36 using 0.8 as a scaling factor

Table 5. Injury Risk Comparison for Fully Powered Air Bags. Belted Hybrid III 5% Female[A] and Unbelted Hybrid III 50% Male Drivers[B] Are in 20 mph Deformable Offset Barrier and 30 mph Rigid Frontal Barrier Vehicle Crash Tests, Respectively. Hybrid III 6-Year-Old Responses Are from Static Test in Reference [1]

	1*	2*	3*	4*
Hybrid III 95% Male				
Hybrid III 50% Male			Head: 0.4% Neck: 0.5% Chest: 0.0%	
Hybrid III 5% Female		Head: 0.7% Neck: 99.4% Chest: 0.0[C]/5.2[D]%		
Hybrid III 6-Year Old	Head: 4.8% Neck: >99.9%			

*1 = Contact with module
*2 = Full Forward (Typical position for Hybrid III 5% Female)
*3 = Mid-Position (Typical position for Hybrid III 50% Male)
*4 = Full rear (Typical position for Hybrid III 95% Male)
(A) Vehicle crash tests from Reference [2]
(B) Vehicle crash tests performed by U.S. automobile manufacturer
(C) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts
(D) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading

Table 6. Injury Risk Comparison for about 25% Depowered Air Bags. Belted Hybrid III 5% Female[A] and Unbelted Hybrid III 50% Male Drivers[B] Are in 20 mph Deformable Offset Barrier and 30 mph Rigid Frontal Barrier Vehicle Crash Tests, Respectively. Hybrid III 6-Year-Old Responses Are from Static Test in Reference [1]

	1*	2*	3*	4*
Hybrid III 95% Male				
Hybrid III 50% Male			Head: 2.1% Neck: 0.8% Chest: 0.0%	
Hybrid III 5% Female		Neck: 3.5% Chest: 0.0[C]/6.4[D]%		
Hybrid III 6-Year Old	Head: 0.1% Neck: 99.8%			

*1 = Contact with module
*2 = Full Forward (Typical position for Hybrid III 5% Female)
*3 = Mid-Position (Typical position for Hybrid III 50% Male)
*4 = Full rear (Typial position for Hybrid III 95% Male)
(A) Vehicle crash tests from Reference [2]
(B) Vehicle crash tests performed by U.S. automobile manufacturer
(C) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts
(D) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading

SENSITIVITY OF OCCUPANT INJURY RISK TO *CHANGES IN CRITICAL PARAMETERS*

The more important parameters that affect air bag system performance as measured by occupant injury risk include deployment time, inflator output, occupant proximity to the air bag module during inflation, occupant belt status (belted or unbelted), crash pulse shape, vehicle velocity change during the crash, occupant category and air bag design. No comprehensive, systematic characterization of the effects of these parameters, considering interactions, on occupant injury risk was found during the course of this study.

To meet a goal of protecting the public from injury during vehicle crashes, air bag performance must be characterized and understood (1) for occupants of different sizes who sit at different distances from the air bag module, (2) for vehicle crashes of differing severity ranging from low speed vehicle to vehicle crashes to high speed rigid crashes, (3) for different ambient temperatures because temperature has a large effect on inflator gas output characteristics, and (4) for belted and unbelted occupants.

The performance of present air bag systems can be severely degraded by variation of any of the parameters mentioned above. The introduction of advanced technology must dramatically increase the robustness of air bag system performance with respect to variation of critical parameters encountered during public usage of automobiles.

Deployment Time. The performance of an air bag system expressed in terms of occupant injury risk is strongly affected by the time at which inflation is initiated, i.e., the deployment time. At the beginning of a crash, an occupant begins to move forward relative to the vehicle. The distance between the occupant and the airbag module decreases as the occupant moves forward. If the deployment time is late in the crash, the occupant can be close enough to the air bag module to interact with the inflating air bag and can experience inflation induced injuries.

Deployment times are shown in Table 7 for six vehicles with conventional air bags tested in deformable offset barrier crashes with 5% female dummies by Transport Canada. The deformable offset barrier crash tests are representative of the "softer" vehicle to vehicle crashes that commonly occur. In four of the tests the deployment time exceeded 40 ms. In those tests, neck injury risk is extremely high, while in the tests with early deployment time the injury risk is low. Late deployment results in the occupant moving into the path of the deploying air bag, increasing injury risk potential.

Results of an unpublished study [3] available to JPL shows that deployment time variability increases inversely with crash severity. That is, as the crash severity is reduced, variability in deployment time increases. Well over 90% automobile crashes occur with vehicle ΔV less than 48 km/h (30 mph), and about 70% of automobile crashes occur with vehicle ΔV between 14 km/h (9 mph) and 35 km/h (22 mph). If late deployment is as prevalent as the Transport Canada tests and the unpublished study would indicate, a substantial number of occupants are being exposed to a significant risk of inflation-induced injury in crashes that commonly occur.

Table 7. Injury Risk of Belted 5% Female Driver (Near Positions) vs. Air Bag Deployment Time In 25 Mile Per Hour Deformable Offse Barrier (DOB25) and 20 Mile Per Hour Deformable Offset Barrier (DOB20) Car Crash. Tests performed by Transport Canada

	Car Model					
	B-96	**F-96**	**E-96**	**G-95**	**D-95**	**Q-96**
	3PB + AB	**3PB + AB**	**3PB + AB**	**3PB + AB**	**3PB + AB**	**3PB + AB**
	DOB25	**DOB25**	**DOB25**	**DOB20**	**DOB25**	**DOB25**
Dummy Response	**TC96-211 100 ms***	**TC96-002 30 ms***	**TC96-025 40 ms***	**TC96-021 91 ms***	**TC95-206 56 ms***	**TC96-024 100 ms***
HIC 15	338	85	112	490	367	240
Injury Risk, AIS 4+, %	0.5	0.1	0.1	1.4	0.7	0.3
Neck Tension, N	4583	1225	1330	4170	2752	2676
Neck Ext. Moment, Nm	134	17	24	45	124	67
Injury Risk, AIS +3. %	>99.9	0.8	1.8	64.2	99.4	62.2
Chest Deflection	37.6	23.1	21.9	25.9	22.4	33.9
Injury Risk[1], AIS 3+, %	3.2	0.0	0.0	0.0	0.0	0.8
Injury Risk[2], AIS 3+, %	23.3	5.7	4.9	7.8	5.2	17.2

3PB = Three point lap/shoulder belt
AB = Air bag
(1) Injury risk is calculated using AIS ≥ 3 rib fractures for distributed chest impacts
(2) Injury risk is calculated using AIS ≥ 3 thoracic injury due to shoulder belt loading

Inflator Parameters. The inflator output gas mass flow versus time profile, the gas molecular weight, and gas temperature all affect the forces exerted on an occupant during an occupant/air bag interaction. Gas is exhausted from the air bag through the bag vent holes, so the rate of pressure rise inside the bag is determined by inflator gas output and vent area. A deploying air bag can cause inflation induced injury during the inflation process when the "membrane effect" occurs.

With depowered inflators, the injury risk for the 50% male is essentially unchanged compared to fully powered air bags. The injury risk for the 5 female is substantially reduced, but the injury risk for he 6-year-old child passenger in close proximity to themodule remains extremely high. For the larger 95% male occupant, no information is available to make an assessment. However, rigid frontal barrier car crash tests indicate that the unbelted 95% male passenger has a comparatively high HIC measurement, which may increase with depowered air bags. Reducing inflator power by about 25% from pre-1997 levels increases robustness of airbag system performance for the 50% male with respect to departures of critical parameters from their design point values established in the RFB 30 crash.

Inflator-to-inflator output variability of inflators with the same specifications appears to be a significant problem. Data made available to JPL from testing of about 50 inflators of the same specifications and from the same manufacturing "lot" show that total gas output and pressure rise rate vary significantly. The minimum "three-sigma" variability of this data is ±13%. Longer variabilities occur during pressure rise. This level of variability would make the benefits of depowering problematic. Inflator output variability of this magnitude would also interfere with the effectiveness of dual-stage inflators as a means of extending air bag protection to higher-severity crashes.

Variability in inflator output will result in variability of measured dummy response. Dummy response measurements from a series of six static tests with an out-of-position 50% male dummy were provided to JPL by an OEM. The tests were performed with six inflators of the same type and from the same "lot" and with the dummy in the same position for each test. The variability of dummy response was significant from test to test. The coefficient of variation (the ratio of the standard deviation to the mean) for the six tests was 39% for neck extension moment, 21% for neck tension, 36% for viscous coefficient (V*C), and 32% for HIC 36. Due to the nature of dummy response, some variation of response measures would be expected even if inflator output did not change from test to test. However, in these six tests inflator output variability is the likely source of the high variability of dummy response.

Proximity. Occupants that are close enough to interact with the deploying air bag as it is being inflated can experience inflation-induced injuries due to the "punch-out" phase of deployment and due to the membrane effect.

The force exerted on an occupant by a deploying air bag increases when an occupant is closer to the module at the beginning of deployment. Static tests with 5% female dummies were performed by Transport Canada to measure dummy response as a function of distance from the air bag module.

Neck injury risk and chest injury risk were established for fully powered and depowered air bag modules for two vehicles.

The neck injury risk for one vehicle with a fully powered module showed an abrupt increase as sternum-to-module distance decreases below 13 cm. The other vehicle showed much lower injury risk. The chest injury risk for the first vehicle also begins to increase at 13 cm, but does not increase significantly for the second vehicle. For both vehicles neck and chest injury risks are much lower with depowered modules. The superior performance of the second vehicle in these static tests is attributable to the air bag module design. The module is recessed in the steering wheel hub, and the air bag initially deploys radially when the occupant is near the module. This implies that the keep-out zone is vehicle and design dependent.

Belt Status. Belts limit the extent to which occupants can move closer to the air bag during a crash. Since inflation-induced injuries are the result of close proximity to the air bag module during air bag inflation, limiting occupant movement toward the module during a crash can greatly reduce occupant interaction with the inflating air bag.

If the initial position of the occupant is sufficiently close to the module, occupant interaction with the inflating air bag is difficult, if not impossible, to avoid. In this situation, the inflating air bag must not exert excessively high forces on the occupant if inflation-induced injuries are to be avoided. In most cases 50% male occupants are at a very small risk of inflation-induced injuries with or without belts unless they are out of position and very near the deploying air bag.

The 5% female normally sits so close to the air bag module that inflation-induced injury with a fully powered module of conventional design is likely to occur even when she is belted. With depowering, 5% female occupants will have low probability of injury risk unless they are out of position and very near the deploying air bag.

Belt use can also provide the opportunity for setting higher deployment velocity thresholds. Since the belts provide sufficient protection in low-severity crashes, higher deployment thresholds, i.e., velocity at which the air bag deploys, could be used for belted drivers.

Crash Pulse and ΔV. Crash pulse shape is extremely important, because it governs the occupant position and motion during the crash. The shape of the crash pulse depends on the car platform and the obstacle being struck. All air bag systems are designed and developed *for specific vehicle platforms.*

A calibrated simulations provided dummy responses and injury risk as a function of vehicle velocity during the crash for fully powered and depowered inflators, for rigid and generic crash pulses, for the 5% female and 50% male occupants, and for belted and unbelted occupants. These simulations were performed with early deployment of the air bag, so the results do not reflect late deployment due to deployment time variability. Neck injury risk for the 5% female remains very small with the depowered inflator at ΔVs from 24 km/h (15 mph) to 56 km/h (35 mph), while it is significant for the fully powered inflator. Neck injury risk for the 50% male is not significant at any ΔV from 24 km/h (15 mph) to 56 km/h (35 mph).

The chest injury risk for both the 5% female and the 50% male is significant due to shoulder belt loading at ΔVs from 24 km/h (15 mph) to 56 km/h (35 mph). Advanced technology belts with load limiters offer potential to reduce chest injury risk due to belt loading.

Occupant Category. Smaller-statured drivers sit closer to the air bag module and are therefore at greater risk of inflation-induced injury. In addition, females and children are more susceptible to neck and chest injury than are adult males.

ADVANCED TECHNOLOGY

Figure 2 is a schematic diagram showing the possible elements of an advanced safety restraint system. Table 8 lists the technologies investigated. Table 9 summarizes the advanced technology characteristics. JPL projected technologies that are being developed and that may be available for model years 2001 and 2003.

JPL projected the technology availabilities based on limited contacts with a limited number of vehicle manufacturers and suppliers. The state-of-the-art of advanced air bag technology is in a high state of flux. The projected technologies, as well as other technologies may advance more or less rapidly than indicated as follows.

Model year 2001. The technologies that are being developed and that may be available for model year 2001 provide both improved information and improved response.

Information

- Crash sensors with improved algorithms that will better discriminate when air bag deployment is necessary for occupant crash protection, and can determine the appropriate inflation level for two-stage inflators.
- Belt status sensors that can detect when an occupant is belted so that the air bag deployment threshold can be raised when belts are in use. (These are currently in use in some cars.)
- Seat position sensors that provide an approximate surrogate measure of occupant size and proximity to the air bag module. They can be used in combination with belt status sensors to determine the appropriate inflator output.

Figure 2. Advanced Safety Restraint System Schematic Diagram

Table 8. Technologies For Advanced Safety Restraint Systems

1. Precrash sensors
   - Visible imaging
   - Single antenna radar
   - Stereoscopic radar
2. Crash severity sensors
   - Single point electronic crash sensors
   - Combined electronic and electromechanical multipoint crash sensors
3. Sensing diagnostics modules and crash detection algorithms
   - Physical based crash detection algorithms
   - Hybrid crash detection algorithms
   - Increased firing loops within modules
4. Occupant type sensors
   - Ultrasonic based
   - Passive and active infrared
   - Electrostatic based
   - Visible imaging
   - Weight based sensors (pressure or strain based)
   - Magnetic and electromagnetic tags for child seats
5. Occupant proximity and motion sensor
   - Passive and active infrared
   - Acoustic Electrostatic
   - Visible imaging
   - Radar
6. Computational systems and algorithms
   - Use of existing crash sensing diagnostic modules
   - New dedicated microcontrollers/processors
   - Variety of algorithms for fusing multi-sensor data sets and making deployment decisions
7. Inflators
   - Non-sodium azide propellants
   - Hybrid inflators
   - Cold gas inflators
   - Multi-stage inflators of all types
   - Tailorable mass flow rate characteristics
8. Air Bags
   - Thinner, more flexible fabrics
   - New lighter weight coatings
   - Simplified sewing patterns
   - One-piece woven bags
   - Use of non-woven materials
   - New shape to reduce OOP passenger loadings
   - Multi-level and continuously variable venting
9. Seat Belt Systems
   - High initial belt stiffness
   - High output pretensioners
   - Multiple limit and continuously variable load limiting devices
   - Improved seat mechanics
   - Integrated seat mechanics
   - Integrated seats and seat belts.
   - Inflatable seat belts
10. Diagnostics or status sensors
    - Hall effect seat belt switches

- Seat belt spool-out sensors could provide additional information about an occupant's size and proximity to the air bag module. These sensors were not mentioned as being part of any current industry use strategy and therefore may not be available by model year 2001.
- Static proximity (occupant position) sensors could identify occupants in the keep-out zone, but will be available only if an aggressive development program is undertaken. They would not reduce injuries to all out-of-position OOP occupants, and they could be "fooled" some of the time.

Response

- Automatic suppression can prevent inflation when sensors determine that an occupant is in a keep-out zone where injuries could occur.

Table 9. Summary of Advanced Technology Characteristics

Technology Item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restraint System	Technology Maturity Readiness Date *
Sensors			
Pre-Crash Sensing	These sensors provide remote sensing (electromagnetic) for early crash severity determination.	The potential here is limited. The ability to determine obstacle inertia has not been determined. The implications of system unreliability are not defined, but they are potentially serious.	These sensors could be available for MY2000.
Crash Severity Sensors	These sensors are electromechanical switches and analog accelerometers for determination of crash severity.	Critical capabilities already have been demonstrated. A move toward analog accelerometers (single point sensors) is underway. This reduces cost/complexity.	These sensors are available now.
Sensing Diagnostic Modules/ Crash Algorithms	Improved algorithms are aimed at reducing discrimination times and unintended airbag deployments. Evolutionary design includes improved hardware compatible with an increased number of sensor inputs and restraint firing loops.	There is unclear potential for significant improvement. Details of current system performance are unavailable to JPL due to confidentiality concerns by companies.	Development here is ongoing.
Belt Use Sensors	These sensors determine whether or not a safety belt is being used.	Hall-type sensors have been developed.	These sensors could be available for introduction into vehicles by MY2000.
Belt spool-out Sensors	These sensors aid in determining occupant size.	These sensors with seat position sensors could provide approximate information of occupant size and proximity, but there is no known plan by industry for their use.	These sensors could be available by MY2001.
Seat Position Sensors	These sensors could be used to estimate driver size and proximity to the air bag and passenger proximity.	These sensors would be a surrogate for occupant presence and proximity sensors, but would only provide approximate information.	These sensors could be available for MY2000.
Occupant Classification Sensors	These sensors measure weight and presence for classification of at-risk occupants.	Weight sensors have fundamental inaccuracies and systemic errors. They have limited utility. Presence sensors show ability for occupant classifications. System reliability requirements are unclear. Child seat tags will provide the required performance. Required retrofit of existing child seats is an impediment.	MY2000 could see availability of weight sensors and presence sensors. Tags are available now.
Occupant Proximity Motion Sensors	These sensors involve remote sensing systems to provide range information between occupants and in-cabin hazards.	These sensors are useful for static OOP detection. The consequences of system unreliability are not well defined. Ultrasonic/IR systems hold the greatest promise. Utility of dynamic proximity information is not well understood at present.	These sensors could be available by MY2000/2001.
Computational Systems/ Algorithms	Such systems record all sensor signals to determine/actuate restraint system response.	These might replace upgraded crash sensor diagnostic modules, as systems requirements expand. Hardware currently is available. Utility of currently envisioned advanced algorithms has not been demonstrated.	These systems could be in use by MY2000.

* Technology readiness dates are those dates when production subsystems could be ready. Implementation into vehicles depends upon the OEMs' decision to include them and their technology deployment schedules, which could add one to three years to the model year readiness dates provided here.

Table 9. Summary of Advanced Technology Characteristics (Continued)

Technology item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restrain System	Technology Maturity Readiness Date *
Inflators			
Non-Azide Propellants	These materials replace sodium azide propellants to improve gas generant properties (i.e., they are smokeless and odorless, and have less particulates and lower temperatures).	These inflators employ lower temperature gas with no particulates. This will permit use of lighter-weight air bag fabrics which improve performance. Simpler inflator designs are possible.	Some non-azide propellants are now used; however, they have higher gas temperatures. LOVA propellants probably will be ready for MY2000.
Hybrid Inflators	These inflators use high-pressure stored gas in conjunction with a pyrotechnic charge.	These inflators have more desirable gas generant properties (i.e., less particulates). There is lower variability in performance.	More use is expected by MY1999. Units with LOVA propellants could be ready by MY2000.
Heated Gas Inflators	These inflators use a combustible mixture of dry air and hydrogen gas under high pressure.	The gas generant is clean and environmentally friendly. These inflators permit use of lighter-weight air bag fabrics to improve performance.	These units are expected to be ready by MY1999.
Multistage Inflators	These systems use two separate inflators packaged as a single unit, or two separate pyrotechnic charges with a single inflator.	These inflators permit stages of air bag deployment depending on crash severity and occupant characteristics. Inflator performance variability could overshadow the potential advantages.	A two-stage inflator could be ready for production in 1998.
Inflators with Tailorable Mass Flow Rate	These systems provide control of inflator output in near real-time.	With appropriate sensor information, this technology would permit control of air bag deployment depending on crash severity and occupant location and characteristics.	These inflators are under development.
Air Bags			
New Fabrics and Coatings	Fabrics and coatings that are more flexible, lighter in weight and have lower permeability are now available.	These fabrics permit use of lower output inflators. Lower mass should reduce punchout forces on OOP occupants. These materials simply bag folding techniques. Lighter weight fabrics are less tolerant of particulates and high temperature gases.	Technology has been demonstrated with inflators having low particulates and lower gas temperatures. These materials could be incorporated with hybrid inflators for MY2000.
New Woven Fabrics and Bag Construction	These materials use controlled fabric porosity and improved weaving techniques to reduce or eliminate bag seams.	Fabrics having controlled porosity with low variability could eliminate the need for discrete vent holes.	This is an evolving technology which could be incorporated as product improvement.
New Bag Shapes and Compart-mented Bags	These alternatives involve air bags with multiple compartments, which inflate sequentially. Bags expand radially during deployment.	The first compartment can be pressurized much quicker to provide early occupant protection, with subsequent compartments maintaining the restraint force. This is especially beneficial to OOP occupants.	This technology could be ready for introduction in MY2000.
New Air Bag Venting Systems	These systems provide multilevel venting systems with discrete holes and continuously variable venting designs. Continuously variable venting designs would be controlled in near real-time based on available sensor information.	These systems provide pre-determined variation in venting depending on bag pressure. They provide rapid inflation of air bag (with no venting) to reduce occupant/ air bag interaction. Continuously variable systems must be developed in conjunction with sensors and control strategies.	Multilevel systems could be available in MY1999. Continuously variable systems are being developed.

* Technology readiness dates are those dates when production subsystems could be ready. Implementation into vehicles depends upon the OEMs' decision to include them and their technology deployment schedules, which could add one to three years to the model year readiness dates provided here.

Table 8. Summary of Advanced Technology Characteristics (Continued)

Technology item	Technology Description and Function	Potential of Technology to Improve the Robustness and Performance of Safety Restrain System	Technology Maturity Readiness Date *
Seat Belt Systems			
Pretensioners	This technology involves high output pretensioners to increase coupling between occupant and seat.	Maximizes ride-down distance for dissipation of the occupant's kinetic energy.	Pretentioners are in some vehicles now. Newer high output devices could be ready in MY1999.
Load Limiting Devices	Single or dual level devices provide a fixed force level over the maximum occupant excursions. Continuously variable load limiter provide a wide variation of forces.	Dual level load limiters can provide two-level selection based on knowledge of the occupant's characteristics. Further adjustability is provided by continuously variable devices.	Load limiters are in some vehicle now. Continuously variable devices could be ready in MY2000.
Inflatable Seat Belts	A portion of the standard three-point belt is inflated to augment the belt function.	These devices offer inflated cushioning and also provide some pretensioning of the seat belt. Air belts are less aggressive than air bags.	These devices could be ready by MY2001.

* Technology readiness dates are those dates when production subsystems could be ready. Implementation into vehicles depends upon the OEMs' decision to include them and their technology deployment schedules, which could add one to three years to the model year readiness dates provided here.

- Two-stage inflators permit relatively soft inflation for lower-threshold velocity crashes and full inflation when necessary for high-threshold velocity crashes.
- Compartmented air bags and bags with lighter-weight fabrics that may reduce the size of the keep-out zone.
- Advanced belts can improve restraint system safety and protectiveness. They may include pretensioners that can provide better coupling of the occupant to the seat for improved ride-down during the crash. Also, they can, to some degree, limit occupant proximity to the air bag module. Load limiters can also improve belt performance by reducing maximum belt loads on the occupant. (Pretensioners and load limiters are currently in some vehicles.)

Model year 2003. By model year 2003, there could be evolutionary changes in some of the systems and the possibility of the introduction of occupant and proximity sensors.

Information

- Crash sensor/control system algorithms will continue to be improved
- Belt use sensors will be widely used already.
- Integrated occupant and proximity sensors could be available that would identify occupants in the keep-out zone or those who would enter it.
- Precrash sensors may be available, but their application requires further investigation.

Response

- Automatic suppression to prevent inflation will be available for use with proximity sensors.
- Multistage inflators to provide more tailored responses for a variety of occupants and crash severities could be available, if needed.
- Bag designs will continue to be improved, permitting a reduction of the keep-out zone.
- Pretensioners and load limiters will be placed in increasing numbers of vehicles. Air belts will be available to improve safety belt effectiveness.

ADVANCED TECHNOLOGY ASSESSMENT

To establish the merits of alternative advanced technologies, we used the injury risk sensitivities, the advanced technology characteristics and conducted case studies based on postulated scenarios for implementation of the advanced technology. (see Figure 3). The potential for advanced technology to reduce air-bag-induced injuries and increase protectiveness was estimated for depowered air bags and technology available in model years 2001 and 2003. The fully powered air bag was the base case for the evaluation; the availability of advanced technologies were as postulated in the previous section.

REDUCTION IN AIR-BAG-INDUCED INJURIES

For model year 1998, depowering of air bags could reduce the air-bag-induced injury risk of normally seated small-statured adults. Limited data suggests that in lower severity crashes, neck injury risk for small-statured adults is significantly reduced. However, in high severity crashes, despite some improvement, neck injury risk for small- statured adults remain unacceptably high, even with depowered air bags. It is not clear if these results are due to individual design or are generic. Also, these air bags will reduce the keep-out zone where deploying air bags can injure out-of-position occupants,

Figure 3. Advanced Technology Evaluation Process

putting fewer of these occupants at severe risk. Remaining at significant risk of air-bag-induced injury are occupants who are still out-of-position within the new keep-out zone, children in the right front passenger seat and infants in rear-facing child seats (RFCS) and forward facing child seats (FFCS). Depowering may result in reduced protectiveness for very large occupants and for occupants in high-severity crashes, but data is not available to JPL to substantiate this statement.

Compared to depowered air bags, the application of advanced technologies in model year 2001 will further reduce the size of the keep-out zone which reduces the risk to out-of-position occupants. This reduction will be due to less aggressive air bag response resulting from improved air bag design and dual inflators that provide more tailored responses. The risks to belted occupants with these second-generation systems will be reduced because of reduced air bag aggressivity, an increase in the threshold speed for deployment, and improvements in belts. The risk to unbelted occupants will be similarly reduced by the changes in air bag performance. Despite these improvements, some OOP occupants will remain at severe risk from deploying air bags, as will children and infants in RFCSs and FFCS in the right front passenger seat.

For model year 2003, further advanced technologies that could be incorporated include more sophisticated integration of proximity and occupant position sensors. The system could then suppress inflation when it has a high likelihood of injuring an occupant in the keep-out zone and provide an appropriate signal for multistage inflators. Further advances in belt and air bag design could be introduced in this time frame.

With these technologies, the only serious risk of air-bag-induced injuries would come from the unreliability of the system. System unreliabilities are expected to result in tens to hundreds of unintended deployments per year. These unintended deployments could have the potential of causing a few serious injuries per year.

Increased Protectiveness. During this assessment, the evaluation of the capability of advanced technology to increase the protectiveness of the occupant protection system was a secondary priority. However, the following observations can be made:

Depowered air bags will reduce the inflation-induced-injuries for small-statured and fragile adults. However, they may also reduce the protectiveness of air bag systems for very large occupants and occupants in high-severity crashes, but JPL had no data to assess this premise quantitatively.

Technologies that are expected to be implemented in model year 2001 have the potential for increasing air bag protectiveness by providing improved sensing that permits an improved air bag response. The capability that sensors provide permit the use of dual-stage inflators that will offer increased protection to very large adults and occupants in high-severity crashes when compared to depowered air bags. The higher level inflator stage offers that increased protection. Advanced safety belts will provide increased protection by better coupling of the occupant to the vehicle (pretensioners) and reduced decelerations (load limiters).

In model year 2003, protectiveness will be increased further by refinements in the air bag response capabilities and additional safety belt improvement.

Data were not available to quantitatively access the combinations of circumstances where air bags might be expected to enhance protection.

Strategies used to reduce air bag inflation-induced injuries include suppression of the air bag deployment. Clearly, strategies used to reduce inflation-induced injuries that result in the suppression of the air bag leave occupants unprotected if they are unbelted.

System unreliability may result in unintended nondeployments and occupants will be unprotected. Based on projected air bag installation and expected 0.99999 to 0.9999 system reliability, the number of unintended nondeployments will be in the tens per year. High system reliability is achievable through diligent effort; the actual number of unintended nondeployments will depend on the effort made to achieve high reliability.

In an advanced restraint system the desired air bag system response will be tailored to perceived occupant and crash attributes in an attempt to enhance the safety and protection of the air bag. However, this more complex decision structure creates additional categories of incorrect air bag system response, i.e., deployment may be desired in a given crash and the air bag deploys, but tailored to the wrong response state due to misperceived occupant/crash attributes.

Crash attributes may be the most difficult to reliably perceive since they are necessarily a prediction of an extremely stochastic event whose attributes are generated during the event. To the extent that perceived occupant/crash attributes produce a different tailored response than the true attributes, air bag safety and protection can be adversely affected. Even ignoring economic issues, it is a major challenge to create a crash prediction system that is sufficiently accurate to rely on for tailored air bag response.

Safety belts are the primary and most effective occupant restraint system and they are used by a large majority of occupants. Safety and protection for belted occupants is likely to be substantially enhanced if advanced air bag designs can be predicated on the use of advanced safety belts and not compromised by accommodation for protection of unbelted occupants. The growing use of safety belts may permit such a design strategy.

TECHNOLOGY ADVANCEMENT NEEDS

The expected improvements in safety and protectiveness of air bags, as described above, must be tempered by the understanding that there are key technology advances to be made.

1. Air bag deployment time variability must be reduced by improvements in the vehicle crush/crash sensor system
2. Inflator variability must be reduced so that dual-stage inflators can be applied effectively
3. System and component reliability must receive diligent attention to achieve the high levels required under field conditions
4. Occupant sensors must be developed that can distinguish between small, medium, and large adults, children and infant seats with high accuracy
5. Position sensors to measure occupant proximity to the air bag module with the required response time and accuracy must be demonstrated

All of the above are the subject of current development; but development, test, and integration of the advanced technologies needs to be accelerated to enable its incorporation into production vehicles.

JPL did not uncover any single technological solution to the problem of air-bag-induced injuries. Improvement of air bags through the application of advanced technology will require a dedicated systems engineering approach.

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